Encyclopedia of Laser Physics and Technology

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Passive mode locking previous | next | feedback

Definition: a technique of mode locking, based on a saturable absorber inside the laser cavity

The general aspects

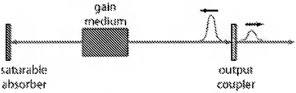


Fig.: Schematic setup of a laser which is passively mode-locked with a saturable absorber mirror, e.g. a SESAM.

of the generation of ultrashort pulses by mode locking are discussed in the article on mode locking. Here, we focus on *passive* mode locking, which can be achieved by incorporating a saturable absorber with suitable properties into the laser cavity. (If the absorber properties are not appropriate, incorporation of the absorber may instead lead to passive Q switching, to Q-switched mode locking, or to some noisy mode of operation.)

We first consider the steady state, where a short pulse is already circulating in the laser cavity. For simplicity, we assume a single circulating pulse (i.e., fundamental rather than harmonic mode locking), and a fast absorber (see below for details). Each time the pulse hits the saturable absorber, it will saturate the absorption, thus temporarily reducing the losses. In the steady state, the laser gain can be saturated to a level which is just sufficient to compensate the losses for the circulating pulse, while any light of lower intensity which hits the absorber at other times will experience losses which are higher than the gain, since the absorber cannot be saturated by this light. The absorber can thus suppress any additional (weaker) pulses as well as any continuous background light. Also, it constantly attenuates particularly the leading wing of the circulating pulse; the trailing wing may also be attenuated if the absorber can recover sufficiently quickly (see below). The absorber thus tends to decrease the pulse duration; in the steady state this effect will balance other effects (e.g. chromatic dispersion) which tend to lengthen the pulse.

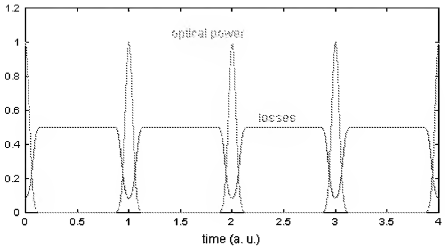


Fig.: Temporal evolution of optical power and losses in a passively mode-locked laser with a fast saturable absorber. The shorter the pulses get, the faster will be the loss modulation. In reality, the ratio of pulse duration to pulse period is usually much smaller than shown here.

Compared with active mode locking, the technique of passive mode locking allows to generate much shorter pulses, essentially because a saturable absorber, driven by already very short pulses, can modulate the cavity losses much faster than any electronic modulator: the shorter the circulating pulse gets, the faster the obtained loss modulation. This holds at least for the leading wing of the pulse, where the absorber is bleached, while absorber recovery may take some longer time.

In many (but not all) cases, the saturable absorber can also start the mode-locking process. If the pulse generation process begins automatically after switching on the laser, this is called self-starting mode locking. Usually, the laser first starts operation in a more or less continuous way, but with significant fluctuations of the laser power (→ laser noise). In each cavity round trip, the saturable absorber will then favor the light which has somewhat higher intensities, because this light can saturate the absorption slightly more than light with lower intensities. After many round trips, a single pulse will remain (principle of "the winner takes all"). However, self-starting is not always achieved. Generally, slow absorbers are more suitable for self-starting mode locking than fast absorbers. For examples, Kerr lens mode-locked lasers are often not self-starting; they run in continuous-wave mode after turning on, and start mode locking only when one knocks against a cavity mirror.

Fast and Slow Saturable Absorbers

If the absorber recovery time is well below the pulse duration, one has a *fast absorber*. In that case, the loss modulation basically follows the variation of the optical power. However, mode locking can also be achieved with a *slow absorber*, having a recovery time above the pulse

duration (see the figure below).

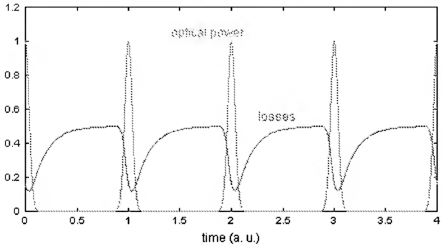


Fig.: Temporal evolution of optical power and losses in a passively mode-locked laser with a slow saturable absorber. The saturable absorber causes a loss modulation which is fast for the leading wing of the pulse, while recovery of the absorber takes some longer time. Passive mode locking can often be achieved even when the recovery time is more than an order of magnitude longer than the pulse duration.

It turns out that e.g. in a solid state laser mode-locked with a slow absorber, there is a temporal range with net gain just after the pulses, where the absorber is still in the saturated state. One should normally expect that such a situation can not be stable, because any noise behind the pulse should exhibit exponential growth of its energy, sooner or later destabilizing the pulse. However, both experimental observations and numerical simulations indicate stability even in situations where the absorber recovery time is more than an order of magnitude longer than the pulse duration. This mystery was resolved first in the case of soliton mode locking (Ref. Kärtner 1995), later also for simple cases without dispersive and nonlinear effects (Ref. Paschotta 2001). In the latter case, a subtle mechanism is responsible for stability: the stronger absorption for the leading edge of the pulse constantly delays the pulse (i.e., shifts the position of the maximum), but not the noise background, so that the latter has a limited time for exponential growth.

Types of Saturable Absorbers

The crucial intracavity component for passive mode locking is a saturable absorber. The most important type of absorber for passive mode locking is the semiconductor saturable absorber mirror, called SESAM. This is a compact semiconductor device, the parameters of which can be adjusted in very wide ranges, so that appropriately designed SESAMs can be used to mode-lock very different kinds of lasers, in particular solid state lasers, including different kinds of semiconductor lasers.

(See also the article on mode-locked lasers.)

Other saturable absorbers for mode locking are based on quantum dots e.g. of lead sulfide (PbS) suspended in glasses. Crystalline saturable absorbers, as often used for passive Q switching (e.g. Cr:YAG), usually have a too slow recovery for mode locking.

There are also various kinds of *artificial saturable absorbers*, based e.g. on nonlinear phase shifts (→ Kerr lens mode locking, additive-pulse mode locking, nonlinear polarization rotation) or on intensity-dependent frequency conversion (→ nonlinear mirror mode locking).

Dispersion and Nonlinearities

In the picosecond regime of pulse durations, chromatic dispersion usually has only a weak effect. Nonlinearities, in particular the Kerr effect, can be significant, depending on parameters like the length and material of the laser crystal, the mode area at that place, and the pulse energy and duration.

For femtosecond pulse generation, one usually requires dispersion compensation, for example with a prism pair, as shown in the article on mode-locked lasers, or with chirped mirrors. In many cases, one operates in the anomalous dispersion regime, where the circulating pulse can be a quasi-soliton; this is called soliton mode locking. In the few-cycle pulse duration regime, with ultrabroad pulse spectra, precise compensation of higher-order dispersion is required.

The effects of nonlinearities, in particular of the Kerr nonlinearity, can also be very important in femtosecond lasers. Excessive nonlinear phase shifts can destabilize the pulses or limit the achievable pulse durations. On the other hand, they can play a useful role in soliton mode locking. In fiber lasers, the fiber nonlinearity is often stronger than desirable and thus often limits the achievable pulse durations and/or pulse energies.

Mechanisms of Pulse Formation and Shaping

In the steady state of a mode-locked laser, the pulse parameters are essentially constant, or at least are reproduced after each cavity round trips. This means that there must be a balance of all effects acting on the pulse. The details of this balance, i.e., the importance of various effects and even the whole principle of pulse formation, can strongly depend on the type of laser and the pulse duration regime, not only on the type of saturable absorber.

To give some examples:

- Gain saturation during the pulse can be significant in dye lasers and semiconductor lasers, but not at all in ion-doped solid state lasers. In the former cases, significant chirp of the pulses can be a consequence. Also, stabilization of the pulse energy by gain saturation is strong in dye lasers and semiconductor

lasers, but very weak in solid state lasers.

- The Kerr effect as well as the effect of dispersion can be negligible in picosecond lasers, particularly for those with multi-GHz repetition rates, but very strong in femtosecond lasers, particularly in fiber lasers. Both can play a very useful role in soliton mode-locked lasers, while much smaller nonlinear phase shifts can have a destabilizing effect in lasers without intracavity dispersion.
- In some mode-locked lasers, the obtained pulse duration strongly depends on the parameters of the saturable absorber. For others (e.g. soliton mode-locked lasers), this influence can be rather weak, because the absorber plays only a stabilizing role, but is not dominant for pulse shaping.

Quite obviously, a comprehensive understanding of the pulse formation and shaping processes is essential for good laser design, with which the best possible performance is achieved. For the detailed study of pulse shaping in mode-locked lasers, numerical pulse propagation modeling can be very useful.

Achievable Pulse Duration

Depending on the particular type of mode-locked laser, the shortest achievable pulse duration can be determined by a number of factors:

- In simple SESAM-mode-locked lasers particularly in the picosecond regime, the pulse duration often results from a steady state between gain narrowing and the pulse-shortening effect of the SESAM absorber, which itself depends on details like modulation depth and degree of saturation.
- In the femtosecond regime, the situation is usually further complicated by the influence of dispersion and nonlinearities. Often one uses soliton mode locking, where the pulse duration is largely determined by the balance of dispersion and Kerr nonlinearity, without a significant direct influence of the gain bandwidth. The pulse duration can then be reduced by reducing the amount of anomalous intracavity dispersion, as long as the circulating pulse stays stable. The stability limit can depend on the gain bandwidth, but also on the total intracavity losses, the strength of nonlinearities and other factors.
- In mode-locked fiber lasers, the achievable pulse duration may also be strongly influenced by nonlinearities or by higher-order dispersion.

The shortest pulses generated directly with a passively mode-locked laser have durations around 5.5 femtoseconds (see the article on ultrafast lasers). External pulse compression allows for significant further reductions.

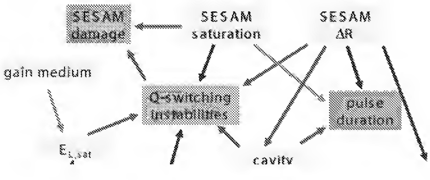
Instabilities

Under certain circumstances, Q-switching instabilities can occur, because the saturable absorber usually "rewards" any increase of the intracavity pulse energy above its steady state value with reduced losses, so that the net gain gets positive and the pulse energy can rise further. The situation becomes unstable if gain saturation is not strong enough to counteract the destabilizing effect of the absorber. Q-switching instabilities (or Q-switched mode locking) can usually be suppressed by observing certain design guidelines, but in certain parameter ranges – for high pulse repetition rates, in particularly in combination with short pulses or high output powers – this can be challenging.

There is also a range of other types of instabilities, which can be related e.g. to excessive nonlinearities, to an inappropriate degree of absorber saturation, to too slow absorber recovery, to higher-order dispersion, to parasitic reflections, or to inhomogeneous gain saturation. It is not always obvious which of these instabilities is at work, but the required measures usually strongly depend on that.

Optimum Design

Optimum design of a mode-locked laser, particularly for operation in extreme parameter regions, must be based on a thorough understanding of the relations between various parameters and effects occurring in such lasers. The figure above shows such relations for passively mode-locked lasers in a very simplified form. For example, a high modulation depth ΔR of the saturable absorber (SESAM) normally leads to shorter pulses, but also to an increased tendency for Q-switching instabilities or Q-switched mode locking, and to a reduced power efficiency. Q-switching instabilities are related in various ways to SESAM damage, and can be suppressed in various ways. With a thorough understanding of all these relations, one can often "shift" the problems to a location where they are much more easily solved. For example, the former research group of Dr. Paschotta managed to solve SESAM damage issues, which originally sometimes occurred even for quite moderate output powers, essentially not by developing SESAMs with higher damage thresholds, but rather by optimizing the overall laser design. This allowed to generate very high output powers without putting the SESAM under excessive stress.



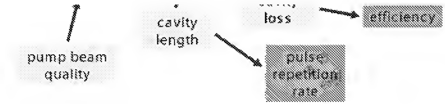


Fig.: Simplified sketch of the relations between various parameters and effects in a passively mode-locked laser. Red arrows indicate positive relations (more of X leads to more of Y), while blue arrows stand for negative relations. A comprehensive understanding of all these relations is required for good laser design, particularly for operation in extreme parameter regions.

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See also: mode locking, active mode locking, mode-locked lasers, femtosecond lasers, ultrashort pulses, double pulses, saturable absorbers, Kerr lens mode locking, self-starting mode locking, additive-pulse mode locking, Q switching instabilities, Q-switched mode locking, pulses, pulse characterization, pulse propagation modeling, carrier-envelope offset, frequency combs, timing jitter

Categories: lasers, methods, pulses